

Reflections of Cluster Assembly in the Stellar Populations and Dynamics of Member Galaxies

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Abstract. We combine optical (HST) and UV (GALEX) imaging of two intermediate redshift galaxy clusters with spectroscopy of member galaxies, to study the relation between the formation history of cluster galaxies and the assembly history of the cluster structure itself. We identify key differences in the large-scale structure and intracluster medium properties of each cluster. In order to assess the importance of cluster substructure and the ICM in the evolution of cluster galaxies, we examine several key indicators of the recent star-formation and assembly history of cluster galaxies. We find that galaxies in cluster MS 0451 ($z = 0.54$) exhibit a markedly lower incidence of recent star formation activity than galaxies in cluster Cl 0024 ($z = 0.39$), likely the result of starvation by the ICM. In addition, Cl 0024 members show evidence for kinematic disturbances that can be linked to the assembly of substructure.

1. Introduction

In general, it is well-known that environmental processes play a significant role in shaping the evolution of galaxies as they assemble onto clusters. With the aid of Hubble Space Telescope (*HST*) imaging and deep optical spectroscopy, recent studies have quantified this evolution in galaxy properties, painting a picture where the fraction of early-type (elliptical and S0) galaxies and the fraction of passive non-star-forming galaxies both grow with time, and at a rate that seems to depend sensitively on the local density of galaxies (Smith et al. 2005b; Postman et al. 2005; Poggianti et al. 2006).

Yet there are a wide variety of physical processes that may be responsible for these evolutionary trends—including galaxy mergers, harassment, gas stripping by the ICM, or tidal processes (e.g. Moore et al. 1999; Fujita 1998; Bekki, Couch, & Shioya (2002)). Observationally, it has so far been impossible to fully separate the effects of the various physical processes, in large part due to the overlapping regimes of influence for each of the proposed mechanisms (see Treu et al. 2003). Further complicating the picture, the large scale assembly states of clusters show considerable variety (Smith et al. 2005a), such that the dominant forces acting on galaxies are likely to vary from cluster to cluster, or over the course of an individual cluster’s assembly history. But gaining an understanding of the complex interplay between a variable ICM, the properties of assembling galaxies, and the overall cluster dynamical state is crucial if we are to have

a complete picture of the growth and evolution of galaxies in a hierarchical universe.

In this contribution, we combine optical (HST) and UV (GALEX) imaging of two $z \sim 0.5$ galaxy clusters with ground-based (Keck) spectroscopy of member galaxies, in an attempt to better characterize the relation between the formation history of cluster galaxies and the assembly history of the cluster structure itself.

2. Observations

We make use of *HST* imaging of Cl 0024 and MS 0451 from the comprehensive wide-field survey described in Treu et al. (2003) and Smith et al. (in preparation). In Cl 0024, HST coverage consists of a sparsely-sampled mosaic of 39 WFPC2 images taken in the *F814W* filter ($\sim I$ band), providing coverage to a projected radius > 5 Mpc. MS 0451 observations were taken with the ACS, also in *F814W*, and provide contiguous coverage within a $10\text{Mpc} \times 10\text{Mpc}$ box centered on the cluster. For both clusters, reliable morphological classification is possible to rest frame absolute magnitude $M_V = -19.5$. All galaxies brighter than this limit are classified visually following Treu et al. (2003).

Cl 0024 and MS 0451 were respectively observed for 15ksec and 80ksec with *GALEX* (Martin et al. 2005) in Oct. 2004 (GO-22; Cycle 1; PI Treu), reaching comparable depths in rest frame *FUV* (observed *NUV*). Galaxy fluxes were measured within $6''$ circular apertures, centered on the optical position, and comparable to the measured *NUV* FWHM ($5''.5$). Observations with the DEIMOS spectrograph on Keck II from Oct. 2001 to Oct. 2005 secured spectra for over 500 members of both Cl 0024 ($0.373 < z < 0.402$) and MS 0451 ($0.520 < z < 0.560$). Details are provided in Moran et al. (2005) and Moran et al. (in preparation). Briefly, we observe with $1'' \times 8''$ slits, with a typical velocity resolution of 50 km s^{-1} , covering rest frame wavelengths from $\sim 3500\text{\AA}$ to $\sim 6700\text{\AA}$. Exposure times totaled 2.5hrs in Cl 0024 and 4hrs in MS 0451. DEIMOS data were reduced using the DEEP2 data reduction pipeline (Davis et al. 2003).

3. Results

3.1. Global Cluster Properties

Similar in their total mass, the two clusters were chosen for study primarily due to their complementary X-ray properties (See Table 1). While MS 0451 is one of the most X-ray luminous clusters known (Donahue et al. 2003), Cl 0024 is

Table 1. Basic Properties of the Clusters

Name	R_{VIR} (Mpc)	M_{200} (M_\odot)	z	L_X (L_\odot)
Cl 0024	$1.7^{(1)}$	$8.7 \times 10^{14} \text{ }^{(2)}$	0.395	$7.6 \times 10^{10} \text{ }^{(3)}$
MS 0451	2.6	$1.4 \times 10^{15} \text{ }^{(4)}$	0.540	$3.8 \times 10^{11} \text{ }^{(4)}$

⁽¹⁾ Treu et al. (2003), ⁽²⁾ Kneib et al. (2003), ⁽³⁾ Zhang et al. (2005), ⁽⁴⁾ Donahue et al. (2003).

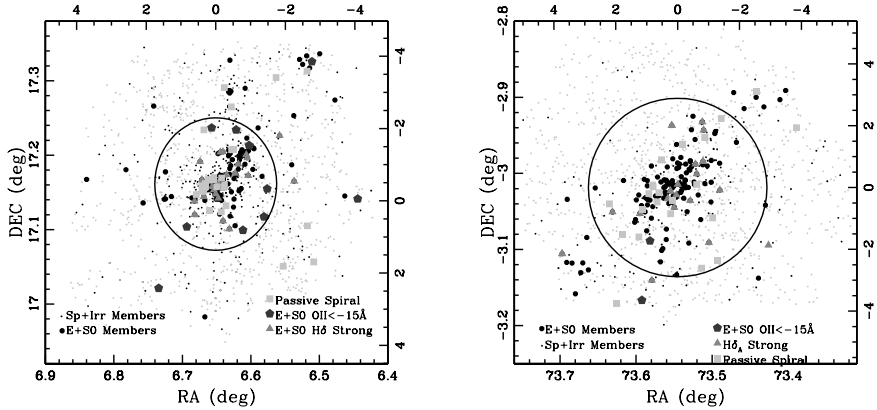


Figure 1. Distribution of galaxies in the field of Cl 0024 (left) and MS 0451 (right). Galaxies showing spectroscopic signs of recent evolution are marked. The distributions of passive spirals are quite different between the two clusters.

somewhat under-luminous (Zhang et al. 2005). This implies a large difference in the density and radial extent of the intracluster medium (ICM) between the two clusters, such that ICM-related physical processes are expected to be significantly more important in the evolution of MS 0451 galaxies. In addition, marked differences in the spatial and redshift distributions of galaxies between the two clusters indicate that the clusters have quite dissimilar recent assembly histories. While the distribution of galaxies in MS 0451 is largely smooth and seemingly well-virialized, Cl 0024 shows obvious signatures of infalling groups (Treu et al. 2003) and, indeed, a recent cluster-subcluster merger (Czoske et al. 2001). In the following, we examine how such differences in the overall cluster environment lead to striking differences in the galaxies themselves.

3.2. Passive Spirals

Passive spirals belong to a class of galaxies that show spiral morphology in *HST* images, but reveal weak or no [OII] emission in their spectra, suggesting a lack of current star formation. Through GALEX UV imaging, we find that passive spirals in Cl 0024 exhibit UV emission nearly as strong as regular star-forming spirals, implying the presence of young stars (Moran et al. 2006). Their unusual combination of UV emission with weak H δ strength supports a picture where passive spirals have experienced a rapid decline and eventual cessation of star formation over the last ~ 1 Gyr. The timescale of this decline implicates “starvation” by the ICM as the likely cause (Bekki et al. 2002) – a process where diffuse gas is stripped from a galaxy’s halo, thereby halting any further accretion of cold gas onto the galactic disk.

In MS 0451, over one third of all spiral galaxies fall into the ‘passive’ category, compared to $\sim 24\%$ in Cl 0024. Of these, 1/3 are detected in the UV (c.f. 2/3 in Cl 0024), suggesting that the typical passive spiral in MS 0451 has fewer young stars than those in Cl 0024. Both effects are likely due to the denser, more extended ICM in MS 0451, which should boost the efficiency of starvation,

and increase rate of passive spiral creation compared to that of Cl 0024. In fact, the spatial distribution of passive spirals across both clusters strongly supports this scenario (Fig. 1). Passive spirals in MS 0451 are spread across a wide area, as expected in the presence of a dense ICM, while Cl 0024 passive spirals are largely concentrated near the cluster core, where its ICM is densest.

3.3. Kinematic Disturbances

By constructing the Fundamental Plane (FP) of Cl 0024, we observe that elliptical and S0 galaxies (E+S0s) exhibit a high scatter in their FP residuals, equivalent to a spread of 40% in mass to light ratio (M/L_V) (Moran et al. 2005). Upon closer inspection, this high scatter appears to occur only among galaxies within 1 Mpc of the cluster core. Outside of this radius, cluster E+S0s follow a tight FP. In contrast, ellipticals in MS 0451 do not exhibit such a high scatter, and no radial dependence is seen. It is therefore likely that the recent merger with a subcluster (Czoske et al. 2001) has disturbed galaxies in the core of Cl 0024, such that they show significant deviations from the FP.

Similarly, in a recent study of spiral galaxies across both clusters (Moran et al. 2007), a large scatter about the Tully-Fisher relation is measured, compared to the field at the same redshift. In Moran et al. (2007), we argue that the large scatter is likely driven by galaxy–galaxy interactions during cluster infall.

4. Discussion

Taken together, our results paint a picture where the fates of infalling cluster galaxies depend heavily on the pre-existing assembly state and ICM density of the cluster. Cluster–subcluster mergers, as seen in Cl 0024, seem to induce departures from the FP, and cluster spirals show signs of similar disturbances. Importantly, passive spirals appear to be surprisingly abundant, suggesting that starvation by the ICM causes a steady decline in star formation rate, driving the eventual buildup of the cluster red sequence.

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